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Quantitative Determinations of Shrub Biomass and Production: A Problem Analysis

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EXECUTIVE SUMMARY

The objectives of this problem analysis were to identify and describe sampling techniques and strategies pertinent to shrub inventory programs currently being developed by the British Columbia Ministry of Forests and Lands. Specific recommendations were developed (1) to quantify levels of forage production available to livestock and wildlife, and (2) to monitor changes in the forage resource.

Levels of forage production should be assessed with annual browse production of leaves and twigs available to browsing ungulates, determined within a double sampling program which includes visual estimates of canopy volume and clipped measurements of browse production. Regression equations should then be developed between clipped browse production and visually estimated canopy volume. Separate regression equations are likely necessary to reflect variation among several factors including site, sampling season, observer differences, and shrub species. The most appropriate transformation and/or regression models can be determined only with preliminary data which confirm the statistical assumptions and functional relationships appropriate for each alternative model.

Changes in the forage resource should be assessed with utilization, determined by measurements of (1) browsed twig diameters at base and point of browsing, and (2) unbrowsed twig diameters at the first measurable internode below the terminal bud. Based upon these measurements, utilization can be derived from post-browsing sampling, without clipping and weighing before and after browsing. No regression equations are required to estimate utilization, as these twig diameter measurements correlate well with percent utilization by weight.

Sampling strategies most appropriate for estimates of annual browse production and utilization should, wherever possible, be consistent with procedures employed by the Ministry of Forests and Lands for rangeland inventory. The inventory area should be stratified to reduce variability of estimates for browse production and utilization within strata. Secondary sample units should be clustered at primary sample units, selected randomly within strata. Within each secondary sample unit, plots for estimates of browse production and utilization should be located systematically along transects, which should occur

within clumps or aggregations of shrubs, if non-randomly distributed. Double sampling for annual browse production should be allocated according to variable probability proportional to size, based upon canopy volume increments.

Sampling for annual browse production, as an estimate of carrying capacity, should occur either at peak browse production or just before the winter browsing period. Utilization should be measured following seasonal browsing by livestock and/or when wildlife leave winter ranges. Estimates of annual browse production should be based on at least 3 years of data. Utilization should be measured approximately once every 5 years, within plots on permanently marked transects.

These recommendations are based primarily upon experimental results, and have not been verified operationally. Preliminary sampling is therefore desirable to confirm relationships among twig diameters, crown canopy volume, annual browse production, and utilization. This preliminary sampling is also required to determine optimal numbers of primary and secondary sampling units, appropriate proportions of primary and auxiliary samples for double sampling, and allocation of clipped browse production plots according to variable probability proportional to size.

Preliminary data may be collected simultaneously with the initial stages of the shrub inventory program. These data must be analyzed immediately so that revised sampling and measurement techniques can be incorporated before the second field season of inventory.

Such preliminary data will also establish whether desired levels of accuracy and precision can be attained at acceptable cost. Shrub measurements vary significantly among a variety of factors, including shrub species, genetic variability within species, plant phenology, moisture content, site conditions, annual growing conditions, position of twigs on shrubs, canopy closure, and response to browsing intensity. In many situations, therefore, accurate and precise estimates of browse production and utilization may be economically prohibitive.

Shrub inventory field personnel should receive a minimum of 1 week's training to minimize variability among samplers and forest districts. Annual browse production and utilization estimates should be restricted to managerially important shrub species.

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INTRODUCTION

The British Columbia Forest Act, revised statutes of British Columbia, 1979, Chapter 140, requires that the "chief forester shall assess the land in the Province for its potential for ... producing forage for livestock and wildlife" (Government of British Columbia 1982). Related to this requirement, the Range Inventory Program of the British Columbia Ministry of Forests and Lands seeks to "provide quantitative and qualitative resource information consistent with the objectives of resource managers as well as to meet Ministry of Forests and Lands legislative mandates" (B.C. Ministry of Forests and Lands 1982). Specific inventory objectives include:

1. to quantify levels of forage production available to livestock and wildlife in a form useful to resource managers.

2. to monitor changes in the forage resource for the purpose of assessing range trend and condition.

3. to provide a means for managing and determining the effectiveness of range management practices in the maintenance and/or improvement of the range resource.

Shrubs constitute an important source of forage for both cattle and wildlife in British Columbia (McLean 1979; Demarchi and Harcombe 1982). Consequently, range inventory must assess shrub as well as herbaceous forage production to allocate available forage among domestic and wild ungulate species. Although a wide variety of shrub production estimates and sampling techniques are available for inventory purposes, each technique displays inherent strengths and weaknesses in satisfying specific inventory objectives and constraints. This report critically reviews literature pertinent to qualitative and quantitative techniques used for shrub measurements and inventory, and provides a basis upon which specific sampling techniques and strategies can be recommended, to meet the requirements for shrub inventory programs in the B.C. Ministry of Forests and Lands.

OBJECTIVES

Specific terms of reference for the problem analysis are to:

1. identify and describe the sampling techniques used to estimate shrub biomass and production.

2. outline sampling strategies, such as simple random, stratified random, multi-stage, multi-phase, double sampling, and ratio estimation, which are used in conjunction with specific sampling techniques to estimate shrub biomass and production.

3. critically evaluate, compare, and contrast shrub sampling techniques in terms of:

    i. specific parameter(s) measured or estimated;

    ii. ability to provide reliable estimates of shrub standing biomass and production, or related auxiliary parameters, at levels of confidence and precision identified by the Ministry of Forests and Lands' Range Inventory Program;

    iii. time and sample number required to accomplish desired levels of confidence and precision;

    iv. potential sources of error, including observer bias, which may result in biased sample estimates; and

    v. relative degree of imprecision and/or bias associated with the sources of error outlined for each technique.

4. provide recommendations regarding:

i. which shrub sampling techniques are readily adaptable to range inventory requirements;

ii. levels of confidence and precision in shrub biomass sampling which can be achieved by range inventory programs;

iii. selection, development, and implementation of a shrub biomass and production inventory program designed to meet management information requirements; and

iv. pertinent research needs for shrub biomass and production sampling within an inventory program.

METHODS

The terms of reference will be addressed primarily with a critical review of literature pertinent to shrub biomass estimation techniques and sampling strategies. Each of the major techniques and strategies will be discussed according to their respective levels of accuracy, precision, and efficiency. Identification of potentially suitable inventory sampling techniques and strategies will be based initially upon the statistical requirements indicated by the B.C. Ministry of Forests and Lands (1984). Recommendations for the techniques and strategies most suitable for shrub biomass inventory programs in British Columbia will then be determined in relation to anticipated fiscal constraints and required sample sizes, to achieve defined levels of confidence and sample error.

Effective management decisions based upon statistical inference from inventory data require that those data be collected with statistical rigour and have known levels of accuracy and precision. Each stage of the inventory process must be well conceived and address specific inventory objectives. By way of background information, therefore, this document includes four primary sections: 1) a review of sampling techniques; 2) a review of sampling strategies; 3) comparisons among sampling techniques and strategies; and 4) recommendations for specific sampling techniques and strategies.

Sampling techniques refer to specific procedures by which shrub parameters may be estimated or measured, while sampling strategies relate to the allocation of sample locations at which inventory data are collected. Assessment of specific sampling techniques will distinguish between those techniques that measure shrub parameters directly, and those that derive or estimate shrub parameters from measurements of auxiliary variables.

A primary purpose of the shrub inventory program is to quantify shrub biomass and production. To describe shrub production accurately, the proportion of current annual growth removed by browsing animals must also be determined. Consequently, the literature review will primarily assess sampling techniques and strategies related to shrub biomass, shrub production, and shrub utilization. Appropriate examples will be drawn not only from shrub inventory sources, but also from literature addressing similar topics in herbaceous plant communities.

Recommendations for specific sampling techniques and strategies will address the presumed major management use of shrub inventory data, namely: to promote informed allocation of shrub production among browsing ungulates.

SHRUB INVENTORY SAMPLING TECHNIQUES

A wide variety of techniques have been developed for collecting shrub information, ranging from simple observations of plant presence to accurate quantification of biomass, production, and utilization. Although estimates of shrub production and utilization are pertinent to wildlife and range managers throughout North America, only a few recent reviews of the topic have been available for consultation in selecting the most appropriate shrub survey methodology (Mannetje 1978; Rutherford 1979; Telfer 1981). Moreover, these reviews necessarily present broad summaries and generalities, which assist the selection of -- but do not identify -- an optimum sampling technique for site-specific purposes and conditions. Nonetheless, these reviews suggest that the following sampling techniques should be considered for potential use within the shrub inventory program of British Columbia.

Reconnaissance Estimates

The Society for Range Management (1974) defines reconnaissance as "a general examination or survey of a region with reference to its main features, usually as a preliminary to a more detailed survey." Generally, reconnaissance surveys visually estimate, rather than directly measure, shrub biomass and associated parameters such as density, crown coverage, and canopy volume (Brown 1954; Zamora 1981).

Aldous (1944) proposed a reconnaissance system that estimated density and utilization of browse on a deer winter range of Minnesota. Sampling occurred in 1/100-acre (0.004 ha) plots at predetermined intervals, wherein density and utilization were both estimated within one of four classes: 0, trace-10, 10-50, and 50-100%. Based upon the mid-point of each percentage class, Aldous (1944) provided calculations for frequency, average density, average degree of browsing, and proportion of total available browse for each woody plant species. These parameters were then combined to provide utilization factors for each plant species, as well as the proportion of browse diet contributed by each. Such information provided guidelines to wildlife managers regarding appropriate deer herd sizes according to the inferred long-term vigour of preferred shrub species.

Stevenson (1982) indicated that reconnaissance surveys comprise the primary method for determining shrub availability and utilization in British Columbia. Ecological classifications within the Ministries of Environment and Parks and Forests visually estimate total canopy coverage of all browse plant species recorded within selectively established plots. Utilization of each browse species is then estimated either by allocation to (1) one of five percentage utilization classifications, or (2) one of eight form utilization classes describing subjective assessments of browse utilization severity (Walmsley et al. 1980).

The classification system described by Walmsley et al. (1980) located sample plots on sites subjectively determined to be in undisturbed climax stages of plant succession. The potential of land management units for shrub production, however, may be enhanced at seral stages of plant succession (Demarchi and Harcombe 1982). Therefore, assessment of current carrying capacity for ungulate use, under prevailing management practices, requires biomass or production estimates of existing shrubs and vegetation within each land management area. The Terrestrial Studies Branch (Ministry of Environment and Parks) currently provides maps that summarize the production capability of mapped units, regardless of successional stage. Five shrub production capability classes are identified, synonomous with percent canopy coverage classes equalling 0-5, 5-10, 10-25, 25-50, and 50-100%, respectively (Demarchi and Harcombe 1982).

Weight Estimation

The suitability of reconnaissance mapping and surveys to assess carrying capacity requires a close correlation between actual shrub production and estimates of shrub production, density, canopy coverage, or some other auxiliary variable. In the simplest form of weight estimation, an observer visually estimates total biomass or production without any direct measurements of yield. Pechanec and Pickford (1937) proposed the first weight estimate technique accepted in statistically critical research. In this technique, observers estimated green weight production of individual herbaceous species within circular plots equalling 1 ft^2 (0.099 m^2). Pechanec and Pickford (1937) concluded that a week of training was sufficient for field samplers to provide accurate, rapid replicated estimates of herbaceous biomass, subject to mechanical verification. Such

accuracy was further enhanced by a periodic assessment of each observer based upon actual clipping of between 10-20% of all estimated plots.

Hutchings and Schmautz (1969) noted three primary difficulties with the weight-estimate technique proposed by Pechanec and Pickford (1937):

1. amount of time required for training individual observers.

2. requirement for double sampling to assess accuracy and provide correction factors for inherent observer bias.

3. effect on estimates by field conditions and observer fatigue or attitude.

To minimize these problems, Hutchings and Schmautz (1969) proposed that estimates of weight be based upon relative-weight estimates, assuming that error is reduced when yield is expressed as a percentage of a standard rather than estimates of actual weight. Five quadrats, approximately 30x60 cm, were randomly located and then arranged such that the central quadrat formed the corner of the four remaining quadrats. Production in each corner quadrat was then estimated as a percentage of that in the central plot. Estimates of total production occurred first, followed by vegetation classes (grasses, forbs, shrubs) and individual species. Hutchings and Schmautz concluded that this method was suitable for estimates of total production, although shrubs were not common enough to provide conclusions regarding reliability for this vegetation class. Moreover, double sampling of some estimated quadrats was still deemed necessary to correct personal observer bias.

Wilm et al. (1944) summarized such a double sampling technique for the weight-estimate method. This double sampling involved visual estimates of green forage biomass on 12.5 ft^2 (1.24 m^2) plots, plus clipped biomass on a subset of these plots. Regression equations were then calculated between clipped and visually estimated plots, accounting for 79, 77, and 72% of the variation in green forage biomass for grasses, forbs, and browse, respectively. These regressions converted all visually estimated green biomass values to actual biomass values, thereby providing more precise and accurate estimates of total biomass for the pasture or land management unit.

Similar results were obtained by Crete and Jordan (1982), who used double sampling to estimate annual browse production of deciduous and coniferous species in southwestern Quebec. Live weight of available browse was visually assigned to one of five weight classes, and then a subset of each weight class was clipped. Reported coefficients of determination for linear regressions of visual estimates upon clipped production ranged between 0.69 and 0.70.

Clip and Weigh Techniques

Shrub biomass can also be measured directly rather than estimated within reconnaissance or double sampling inventory programs. Shepherd (1962), Shafer (1963), Mannetje (1978), Rutherford (1979), and Telfer (1981) all briefly summarized these direct measurements in which shrubs are clipped within plots selected randomly or systematically. Plant material is then usually oven dried to obtain standardized biomass per unit area of shrub biomass, production, or availability.

Rutherford (1979) characterized direct measurement of shrub biomass as "laborious, expensive and destructive", a conclusion shared by virtually all other authors. Consequently, clip and weigh techniques are seldom used exclusively in extensive inventory programs, but are confined primarily to intensive or specific research endeavors (Krefting and Phillips 1970; Blair 1971; Blair and Feduccia 1977; Menaut and Cesar 1979), or in conjunction with other sampling techniques such as regression estimates.

Regression Estimation

Regression estimates reduce the arduous, expensive, time-consuming aspects of direct measurements of shrub biomass by predicting biomass from associated, more easily measured shrub parameters. Biomass of leaves, twigs, or entire shrubs have been associated with: stems per unit area (Shafer 1963; Halls et al. 1970; Knierim et al. 1971; Wolff 1978); twig diameter (Telfer 1969b; Peek et al. 1971; Grigal and Ohmann 1977; Provenza and Urness 1981; Felker et al. 1982); stem or trunk diameter (Baskerville 1965; Schuster 1965; Telfer 1969a; Brown 1976; Ohmann et al. 1976; Harrington 1979; Guy 1981; Felker et al. 1982); shrub height (Peek 1970; Ohmann et al. 1976; Harrington 1979; Felker et al. 1982); crown volume (Peek 1970; Burk and Dick-Peddie 1973; Moore and Bhadresa 1978; Bryant and Kothmann 1979; Guy 1981; Murray and Jacobson

1982); crown diameter, depth, and density (Dean et al. 1981); crown width (Rittenhouse and Sneva 1977); crown area or cover (Peek 1970; Ohmann et al. 1976; Murray and Jacobson 1982; Anderson and Kothmann 1982); height and stem diameter products (Bobek and Bergstrom 1978; Crow 1978; Crow and Laidly 1980; Stone and Crawford 1981); twig lengths (Schuster 1965); twigs per plant (Schuster 1965; Peek 1970); and shrub ring widths (Davis et al. 1972).

These simple and multiple regression estimates have generally assumed one of four mathematical models, including linear, quadratic, semi-log, and log-log relationships. The most appropriate mathematical model for shrub biomass estimates varies with a number of factors and criteria -- such as sampling strategy, predictor variables, spatial distribution of shrubs, shape of shrubs, sample size, range of data values, distribution of variances for sample means, and regression estimates -- and with the biological relationship between shrub biomass and the predictor variables.

Density Measurements

Most shrub inventory programs seek to provide estimates of biomass or production available for ungulates on a land area basis. Consequently, the density of shrubs per unit area may also be required in association with either direct measurement of shrub biomass and production, or with associated shrub parameters used for regression estimates of shrub biomass and production. Such density assessments have been used extensively to evaluate ecological dominance, and are often obtained directly by counting or estimating all those shrubs of interest, rooted within systematically or randomly located plots (quadrants).

Density based upon plots, however, is often viewed as undesirably laborious because of time required for plot location and establishment (Cottam and Curtis 1956). Theoretically, the density of shrubs is inversely proportional to the distance between individual shrubs, such that density can be assessed by measuring distance between randomly selected pairs of individuals along transects, rather than within plots (Cottam 1947; Cottam and Curtis 1949; Curtis and McIntosh 1950). Such plotless techniques reduce the amount of time required to provide similarly precise estimates of shrub density, presence, or contagion compared to estimates obtained from plots.

Many techniques have been developed for determining density without plot establishment, based either on point-to-plant or plant-to-plant distances. For

example, the closest-individual method measures distance from a sample point to the closest woody species, while nearest-neighbour techniques calculate average distance from each individual in the population to its closest neighbour (Cottam and Curtis 1956). The random-pairs method (Cottam and Curtis 1949; Cottam et al. 1953) selects the closest woody plant to a stratified sample point. A 90° exclusion angle is then erected on either side of a bisecting line between the sampling point and the closest woody plant. The second individual of the random pairs is that woody species closest to the first individual, but outside the 180° exclusion area. The distance between these two individuals is then measured. The point-centered quarter estimate of shrub density averages four distances measured from a sample point assumed to be the centre of four quadrants around the sample point. Distances are recorded from the point to the closest shrub in each of the four quadrants (Cottam et al. 1953).

Several variations of these techniques have been developed to facilitate random selection of shrubs, to overcome non-random spatial distribution of shrubs in the landscape, and to produce unbiased estimates of shrub density. Batcheler's (1971) corrected-point-distance measures three distances, including that from the sampling point to the nearest plant, that from the nearest plant to its nearest neighbour, and that from the second plant to its nearest neighbour. Random selection of shrubs assumes their random distribution in the landscape. Consequently, the point-to-nearest-plant is an unbiased estimate of density when shrubs occur randomly, but biased if shrubs are uniformly or contagiously distributed. Such bias is corrected with an exponential function of the sum of point distances divided by the sum of the nearest neighbour distances when first-order contagion of shrubs occurs. Secondary clustering of shrubs within first-order clusters requires division by the sum of second-neighbour distances (Batcheler 1971).

The angle-order method (Morisita 1957) also provides unbiased density estimates for non-randomly distributed shrubs. This technique divides each sample location into four adjacent quarter circles with radii equal to measured distances to the third (or more) nearest individual. Even when shrubs are distributed irregularly over the whole circle, individuals are assumed to be more uniformly or randomly distributed within each quarter circle. Two estimates of density are then obtained. The first (d_1) is based upon whole circle density calculated by summing quarter circle densities, while the second (d_2) results

from an average density among all four quarter circles. If shrubs are uniformly or randomly distributed over the whole area (d_1 less than d_2), then d_1 and d_2 are both estimates of the true population density, which is then obtained by the average of d_1 and d_2. If the summed density (d_1) exceeds the average density (d_2), then d_1 becomes the best estimate of irregularly distributed shrub density.

SHRUB INVENTORY SAMPLING STRATEGIES

The previous section summarized those techniques available for collecting shrub data following selection and location of sample units. Such sample units usually occur in vegetation displaying high diversity in species composition, community structure, and spatial distribution. Appropriate sampling strategies or placement of samples must therefore reflect such plant community diversity so that unbiased estimates of sample parameters can be obtained (Barnes 1976; Zamora 1981). Attempts to select representative sample units subjectively often produce biased results (Jolly 1954; McIntyre 1978), corresponding primarily to the experience, preconceptions, and motivation of sampling personnel. Moreover, subjective placement of sample plots invalidates estimates of variability required for determining precision of sample means (Jolly 1954). To overcome these problems, a variety of sampling strategies have been developed for ecological and inventory purposes, and generally include various refinements of simple random sampling, stratified random sampling, systematic sampling, multi-stage sampling, multi-phase sampling, and variable probability sampling.

Simple Random Sampling

Simple random sampling allocates samples at random within a plot or geographic survey area. All possible placements of samples are provided an equal chance of being selected. From the sampling area, which is usually divided into a grid whose coordinates describe sample units of equal sizes, specific sample units are selected with a random number table or equivalent technique (Jolly 1954; McIntyre 1978).

A major statistical advantage of simple random sampling compared to subjective sampling is that sample variances represent unbiased estimates (McIntyre 1978). Strictly random sampling for inventory purposes, however, produces large sample variances which can be reduced only by increasing sample size (Lyon 1968). As this sample size is usually prohibitive economically, simple random sampling is virtually never suitable for management oriented, extensive shrub inventory programs.

Stratified Random Sampling

Stratified random sampling first subdivides the area to be sampled into relatively homogenous blocks or strata. Each stratum corresponds to uniform characteristics of population parameters such as shrub species or forest cover type. Random samples within each stratum provide estimates of sample means with smaller sample variances, compared to simple random sampling. Consequently, appropriate sample size, based upon desired levels of statistical confidence and sample variance, is also reduced compared to that in simple random sampling (Lyon 1968; McIntyre 1978).

Next, average estimates of shrub parameters for the entire inventory or sample area are obtained by combining data from each stratum, assuming such data are weighted according to the proportion of each stratum of the whole sample area. Sampling intensity in each stratum need not be constant, but should seek a compromise between (1) minimum required precision and accuracy for each stratum mean, (2) increased sample sizes associated with more variable strata, and (3) cost of data collection. The efficiency of stratified random sampling relative to simple random sampling equals plot variance for random sampling divided by sub-plot variance averaged across all strata. Estimates of sampling error for stratified random sampling requires at least two random estimates within each stratum (McIntyre 1978).

Stratified Sampling Using Ranked Sets

McIntyre (1952) introduced ranked set sampling as a specific stratified sampling technique to estimate herbage production in large areas or pastures. Subsequently, Halls and Dell (1966) used ranked set sampling for shrub production estimates, while Dell and Clutter (1972) provided a statistical verification of this sampling strategy.

Ranked set sampling employs visual ranking to obtain estimates of population means. At each sample point, groups of quadrats (usually three) are placed systematically relative to the sample point. At each group of quadrats, termed "sets", the parameter of interest is ranked visually from highest to lowest. In the first set, the highest ranked quadrat is then quantified by clipping for biomass production. In the second set, the median quadrat is clipped, while the lowest ranking quadrat is clipped in the third set (McIntyre 1952, 1978).

Sufficient sets are processed to yield a predetermined number of quantified samples and a mean for each ranking.

Similar to stratified sampling, the average of ranked set means produces an unbiased estimate of the population mean (Dell and Clutter 1972). Errors in ranking quadrats, however, reduce precision compared to random sampling. Precision of estimates within ranks is improved by allocating the number of clipped quadrats in proportion to the standard deviations of rank sub-populations (Halls and Dell 1966; Dell and Clutter 1972). Small variation within ranked sets reduces the value of this sampling strategy, particularly when the population parameter displays strong, quantitative gradients throughout the entire inventory area. To overcome this difficulty, the inventory area should be divided into strata with relatively homogenous population gradients (McIntyre 1978).

Systematic Sampling

Systematic sampling collects information more quickly, and therefore less expensively, than either simple random sampling or stratified random sampling. Only an initial starting point or sample location is established randomly, with subsequent samples located at predetermined, regular intervals, often along transects. Such systematic selection of sample locations permits increased numbers of samples per unit time by eliminating random location and establishment of each sample point. Systematic sampling may occur within strata, which usually represent inventory units known to contain the population parameters of interest.

Systematic sampling is commonly used in extensive field surveys, even though lack of complete randomization precludes a statistically unbiased estimate of sample variance (Cochran 1977). In his review of sampling techniques, however, McIntyre (1978) concluded that the degree of bias in the estimate of error derived from systematic samples is small, particularly relative to efficiencies in time and labour. Moreover, Cochran (1977) indicated that systematic sampling, with samples spread more evenly over the population, is considerably more precise than stratified random sampling.

Multi-Stage and Cluster Sampling

Multi-stage sampling is commonly employed in surveys where the cost of travelling to sample locations constitutes a major inventory expense. Ideally,

therefore, more samples are collected at each of a reduced number of primary sampling locations, thereby providing estimates of population means with prescribed levels of precision at least cost (Cochran 1977; McIntyre 1978). Primary sampling locations within inventory programs are usually determined randomly within land units demarcated by a grid. Each of these primary sample units is then subdivided into secondary sampling units, normally located on a regular pattern within each primary unit. Partitioning of sample units may proceed further to tertiary units or beyond, depending upon inventory objectives and costs. A random sub-sample of the secondary units is then taken in each of the primary units, with this sub-sampling proceeding to the lowest level of partitioning (Watts 1983). Systematic rather than random sub-sampling provides additional sampling convenience and savings in travel costs. Cluster sampling is a single-stage sampling design in which all secondary units of the randomly selected primary units are sampled (Watts 1983). Clustering offers reduced sampling travel costs, although sampling precision is also usually reduced (Titus 1979; Watts 1983).

The overall mean for the inventory area is obtained from the primary sampling means weighted according to sample size (McIntyre 1978). The sampling error associated with estimates of population means determined with multi-stage sampling depends upon randomization techniques employed at each sample stage for each sample mean. If simple random sampling is used at all stages of sampling, then the sample mean obtained from the lowest stage is an unbiased estimate of the population parameter at that stage. Similarly, the variance of the population mean can also be estimated without statistical bias, assuming simple random sampling at all stages (Cochran 1977).

Multi-Phase and Double Sampling

Multi-phase sampling consists of selecting a large, preliminary sample of an auxiliary variable which can be measured relatively inexpensively (Cochran 1977; Nichols 1979). A subset of the first phase sample units is then selected for accurate measurements of the primary variable. Regression or ratio estimates are developed between the auxiliary predictor variable and the primary variable of managerial interest. Many operational examples of multi-phase sampling exist in forest inventories, with basal area used as an auxiliary variable for predicting timber volume. Auxiliary and primary variables may also be ex-

pressed in the same units, such as when aerial photo estimates of timber volume are used as an auxiliary variable for ground measurements of timber volume (Nichols 1979). Multi-phase sampling assumes that the auxiliary variables can be estimated easily, with much less cost than the primary variable (Cochran 1977; Nichols 1979).

Multi-phase sampling may include two or more phases, of which two-phase sampling, or double sampling (Wilm et al. 1944; Crete and Jordan 1982), is a commonly used subset (Cochran 1977). Multi-phase differs from multi-stage sampling in that a regression equation is developed between auxiliary variables sampled during phase one, with primary variables sampled at subsequent phases. In multi-stage sampling, sufficient primary data are collected at the finest stage of resolution, precluding the need to even collect auxiliary information at higher stages of resolution. Multi-stage and multi-phase sampling may complement each other. Two-phase (double) sampling can be used to gather data at the finest stage of resolution in a multi-stage sample.

If reduction of sampling effort is the primary objective of multi-phase or double sampling, then the correct proportion of clipped to estimated plots must be calculated prior to the field season. Too many clipped plots provides unnecessary expense, while too few produces unreliable regression estimates (Brown 1954). Cochran (1977) further cautioned that first-phase estimates of the auxiliary variable necessarily reduces inventory funds and subsequent sample units which can be committed to the primary variable. Multi-phase or double sampling is therefore profitable only if the gain in precision from ratio or regression estimates more than offsets the loss in precision due to the reduction in sample size of the primary variable.

Cochran (1977) provides formulae for determining the relationship between savings in cost of sampling and subsequent required correlation between the estimated and measured parameters. For example, if cost of estimating production parameters equals 1/10 of that for direct measurements, then double sampling provides financial benefits only if r^2 of the regression line exceeds 0.33 (McIntyre 1978). Wilm et al. (1944) further warned that the advantage of double sampling may disappear entirely in situations where travel time between sample points is so large that the additional cost of clipping all plots would form a small proportion of total field time.

Variable Probability Sampling

Sampling of extensive populations, such as shrubs, often results in primary, secondary, or stratified sample units that differ in size or values of population variables. In such situations, selections of sample units with equal probabilities may result in biased results, whereas selection with probabilities proportional to size is more efficient economically, and statistically unbiased (Cochran 1977).

Examples in forestry include (1) 3P sampling in which trees are selected with probability proportional to predicted values; (2) prism sampling in which trees are selected with probability proportional to basal area; and (3) triangle sampling in which trees are selected with probability proportional to occupied ground area (Watts 1983). No examples of shrub populations sampled with variable probabilities were found in the literature, perhaps because variable sample unit sizes or population values must be known or approximated before sampling (Cochran 1977).

COMPARISONS AMONG SAMPLING TECHNIQUES AND STRATEGIES

The most appropriate sampling techniques and strategies for shrub inventory programs depend upon a variety of criteria, notably (1) selection of sampling units suitable to meet inventory and management objectives, (2) difficulty in obtaining statistically reliable estimates of carrying capacity and forage allocation based upon shrub measurements, (3) desired levels of accuracy and precision, (4) the spatial arrangement of shrubs within the sampling unit (Shafer 1963; Rutherford 1979), and (5) the appropriate shrub parameters to sample. The following discussion assesses these considerations relative to shrub inventory in British Columbia.

Appropriate Assessment Parameters

Appropriate shrub measurement and assessment parameters depend primarily upon management and inventory objectives. For example, Rutherford (1979) concluded the amount of browse available to specific animals within a particular time period constitutes the ultimate objective for most estimates of shrub biomass and production. The term "browse", often inconsistently applied to a variety of shrub parameters, is used here to describe that part of annual leaf and twig growth of shrubs, woody vines, and trees which is potentially available for animal consumption. Utilization of this browse is obviously pertinent to the Ministry of Forests and Lands' inventory objectives for (1) making inferences regarding trends in range condition, and (2) assessing effectiveness of range management programs.

Estimates of annual browse production per unit area are also essential to derive proper animal stocking rates, and to allocate annual production among browsing animal species. Consequently, annual production must either be measured or estimated directly, or must be derived from known, verifiable correlations with auxiliary parameters such as canopy volume. Moreover, if annual production is based upon measurement of individual shrubs, then shrub density is also required to provide estimates of annual production per unit area. Production, density, and utilization must therefore all be considered for inclusion within the shrub inventory program. The section that follows compares sampling

techniques and strategies for each of these parameters, as well as for shrub biomass.

Appropriate Techniques for Estimating Biomass and Production

Clipped measurement of either biomass or annual production of shrubs is extremely time consuming and laborious, and is consequently inappropriate as the sole means of quantifying biomass or production within inventory programs (Shafer 1963; Barnes 1976). For example, production estimates of browse and leaves up to a height of 1.5 m within 20% of the sample mean, required 28-158 one-square metre plots in scrub oak-pine communities of the southeastern United States (Harlow 1977). Sampling rates, however, for plots clipped to a height of 1.5 m averaged only 9 plots per man-day and ranged from 5 to 25. Consequently, biomass and production are more often obtained by other techniques such as visual estimation or regression with associated shrub parameters, which may be measured more readily than shrub biomass.

Pechanec and Pickford (1937) concluded that visual weight estimates of herbaceous vegetation provided accurate information about actual biomass, although personal bias differed significantly among three observers. No information was provided on estimation of shrub biomass. Wilm et al. (1944) also investigated visual weight-estimate techniques and reported satisfactory precision for production (green forage) estimates of grasses and forbs, although the sampling error for estimates of browse production was unacceptably high.

Shafer (1963) compared weight estimation with clip-and-weigh and the twig count method, which converts a count of twigs to twig weights by use of an average weight per twig for individual species. No significant differences in accuracy occurred among these three techniques. Although weight estimation procedures required only 3.2 minutes per plot compared to 4.6 and 21.8 minutes for twigs counts and clip-and-weigh, respectively, variability among the four observers was significantly higher for weight estimation than either clip-and-weigh or twig count methods. The twig count method also proved ineffective, as no statistically significant correlation existed between twig counts and actual twigs per plot for two of the observers. Twig counts for the remaining two observers accounted for only 24% of the variability in actual twig numbers per plot. Schuster (1965) demonstrated that twig counts showed the poorest

correlation with current season twig and shoot weight, compared to twig length and stem diameter.

Hutchings and Schmautz (1969) proposed that weight estimates as percentages of base plots may be more accurate than biomass or production estimates expressed directly in weight units. Generally, all four observers estimated herbaceous production within 20% of the acutal mean, while estimates of forage classes and individual species were more variable. On sites supporting abundant shrubs, correlation coefficients between actual and estimated shrub production equalled 0.99 for all four observers, although estimates of production ranged between 80 and 116% of actual shrub production. Hutchings and Schmautz (1969) concluded that relative weight estimation appeared most suitable on ranges where vegetation is uniform and mono-specific.

Unfortunately, shrubby vegetation in British Columbia is usually neither uniform nor mono-specific. The highly variable growth form of shrubs compared to herbs also appears to limit the precision and accuracy of visual shrub biomass and production estimates, as implied by this review's inability to find any literature recommending this technique on an extensive basis. Indeed, Shafer (1963) recommended against the use of visual weight estimation for inventory purposes.

Regression techniques offer a necessary and useful compromise between clipping and visual estimates of shrub biomass and production. The following discussion summarizes the relatively voluminous literature dealing with regression estimates of shrub biomass and production, emphasizing the authors' respective conclusions regarding (1) goodness of fit of their regression equations, and (2) general applicability of their equations to shrub inventory programs. Direct comparison among conclusions, however, is unwarranted for several biological and statistical reasons. For example, these studies varied tremendously by geographic region, plant community, plant species, and sampling period. Moreover, most authors assess their regression equations, at least partially, with coefficients of determination (r^2), which are not directly comparable among different data sets, or with different forms of response variables and regressions such as linear, log, and allometric. Consequently, the following discussion identifies the gamut of available regression equations, and suggests, through inference and deduction, which shrub dimensions are most promising for predicting shrub biomass and production in British Columbia.

Ohmann et al. (1976) reported allometric regressions of five shrub biomass and production indices upon eight associated shrub dimensions, and concluded that stem diameter was the overall best predictor variable, as assessed by minimum error associated with each combination of variables averaged among five shrub species. Stem and total aboveground biomass regressed upon stem diameter commonly produced r^2 values between 0.83 and 0.93, with somewhat lower values (0.47-0.80) for leaf and twig biomass. Leaf biomass was generally predicted better by crown area, with r^2 values ranging between 0.66 and 0.86.

Brown (1976) also developed allometric regressions of total aboveground biomass upon basal stem diameters, and similarly reported high average r^2 values of 0.91 and 0.74, respectively. High coefficients of variation for biomass per square metre (60-340%; average = 152%) required at least 20-50 one-quarter milacre (4.05 m^2) plots to furnish standard errors of the estimate within 20% of the mean. Telfer (1969a) regressed total aboveground weight (stems and leaves) and leaf weight of 22 woody species on stem diameter at ground level, and reported r^2 values ranging between 0.74 and 0.96.

For multi-stemmed shrubs, Harrington (1979) reported that log-log regressions of leaf and wood weight on stem heights produced higher correlations with lower errors of the estimate, compared to regressions on stem diameter. He cautioned, however, that such equations could not be used safely in other plant communities because of variability in plant density and shading. Although Felker et al. (1982) discounted stem height of tree legumes as too difficult to measure, Ohmann et al. (1976) believed shrub height to be measured easily to the nearest 15 cm. Coefficients of determination ranged primarily from 0.50 to 0.60, with the highest r^2 of 0.70 obtained for the regression of leaf biomass on plant height. Such values are similar to those obtained by Peek (1970), who identified correlation coefficients of 0.76-0.88 (r^2 = 0.58-0.77) for log-log regressions of leaf and twig production on plant height.

Regarding plant height, Peek (1970) reported higher correlations for leaf and twig production with numbers of twigs, canopy area, and canopy volume. Canopy area was calculated from the formula for area of a circle and of an ellipse, while plant volumes were calculated by multiplying canopy area by shrub height. Shrub measurements included maximum shrub height and two diameters taken at right angles to each other, one of which was maximum shrub canopy diameter. Numbers of twigs, canopy area, and canopy volume were all highly

correlated with production parameters, as correlation coefficients ranged between 0.86 and 0.97 (r^2 = 0.74-0.94). No significant differences in regressions for each of three woody plant species occurred between sites, primarily because of site similarity upon which the regressions were based. Peek cautioned, however, that regressions were relevant only to those sites from which they were obtained. Approximately 25 clipped plants were needed to provide reliable regressions for canopy area with weight. Such a sample required 1 hour, and provided regression coefficients accurate to within 10, 13, and 18% of the point estimate at the 95% level of confidence for the three species, respectively. Ohmann et al. (1976) also obtained good allometric regressions of total above ground biomass with crown area, as r^2 values for mountain maple (Acer spicatum) and willow (Salix spp.) equalled 0.89 and 0.91, respectively. Allometric regressions of total biomass with crown area for green alder (Alnus crispa) and juneberry (Amelanchier alnifolia), however, equalled only 0.48 and 0.61, respectively.

Rittenhouse and Sneva (1977) regressed biomass of big sagebrush (Artemisia tridentata) upon crown width and elliptical crown area, producing r^2 values between 0.73 and 0.90, depending upon various logarithmic expressions. Combining crown width with height in multiple regressions improved these relationships to 0.94 and 0.97, respectively. Dean et al. (1981) similarly demonstrated high coefficients of determination for log-log multiple regression equations of sagebrush production on crown diameter, crown depth, and crown denseness (ocularly estimated percent of foliage within the shrub crown). Although Dean et al. (1981) stated that such characteristics are readily identified and easily measured, no estimates of time requirements were provided.

Moore and Bhadresa (1978) and Guy (1981) both estimated shrub biomass by regressions upon measurements of crown volume, although neither provided r^2 values for their equations. Peek (1970), Burk and Dick-Peddie (1973), Bryant and Kothmann (1979), and Murray and Jacobson (1982) similarly estimated shrub biomass or production as a function of crown volume measurements, with generally high r^2 values reported for all four investigations. Coefficients of variation varied widely, however, depending upon plant species and form of regression model (Bryant and Kothmann 1979; Murray and Jacobson 1982), while no estimates of sampling time were provided by any of the above studies.

The product of stem height by stem diameter has also been used to estimate biomass and production. Crow (1978) and Stone and Crawford (1981) generated r^2 values of 0.99 and 0.95-0.97, respectively, although neither author provided assessments of variability or time requirements. Bobek and Bergstrom (1978) obtained similar r^2 values between 0.92 and 0.96 for annual production regressed upon diameter x height, although coefficients of variation ranged between 36.5 and 300.0%, virtually eliminating the utility of the regression line. For example, to obtain reliable results for individual species, regression estimates required 77-533 three by five-metre plots, although total annual production available from all five species combined could be estimated by regression based upon only 21 plots, providing a 95% confidence interval within 20% of the sample mean. Comparable precision for estimating annual production by clipping required samples from only 17 plots. However, Bobek and Bergstrom (1978) reported that two persons needed 1,480 minutes to clip two plots, compared to only 135 minutes to collect diameter, height, and twig count measurements, thereby producing a considerable savings in time for comparable accuracy.

High correlations between twig weight and twig diameter have also been reported by many authors (Shafer 1963; Schuster 1965; Basile and Hutchings 1966; Telfer 1969b; Lyon 1970; Peek et al. 1971). Such correlations and associated regressions of twig or shoot weight on twig diameters have been developed primarily to estimate utilization, and are therefore summarized in the section dealing with appropriate techniques for estimating utilization.

Summary

Bobek and Bergstrom's (1978) summary of sample time to clip-and-weigh illustrates that inventory of shrub biomass or production can not be based realistically upon clip-and-weigh techniques alone. Alternatively, weight estimates require extensive training, yet still exhibit bias among observers, with imprecise estimates. As well, visual estimates are clumped about individual means (Pechanec and Pickford 1937), and are not strictly subject to statistical analysis (Shafer 1963). Consequently, although visual weight estimates are tempting for inventory purposes because of extraordinary savings in sample time, they should be used with caution, and are most appropriate in vegetation types displaying physiognomic uniformity and low species diversity.

Measurement of associated shrub characteristics for regression with biomass or production offers a compromise between direct measurement and weight estimation. Virtually all associated measurement parameters investigated have produced high coefficients of determination, and presumably provide potential for inventory purposes in British Columbia. None, however, can be recommended as the best, because of extreme variations due to site, species, and environmental variability. Furthermore, data on time requirements for sampling of associated shrub parameters are incomplete, precluding a recommendation based upon savings in time. Although height-diameter products provided high r^2 values with documented large savings in sample time, Bobek and Bergstrom (1978), Crow (1978), and Stone and Crawford (1981) all described trees and shrubs with predominantly single stems. Thus, their success may not be appropriate for the variety of multi-stemmed species in British Columbia. Unfortunately, high correlations between stem height and biomass presented by Harrington (1979) for multi-stemmed species were not repeated by other authors investigating stem height. In contrast, canopy volume and area measurements provided relatively consistent high r^2 values for regression with biomass and production, and therefore have the greatest potential for inclusion in British Columbia shrub inventory programs.

Appropriate Techniques for Estimating Canopy Area and Volume

Walmsley et al. (1980) and Demarchi and Harcombe (1982) both recommended visual estimates of shrub canopy cover in British Columbia resource inventory programs. Although no documentation is provided regarding the accuracy of estimates, Demarchi and Harcombe (1982) reported that field experience verified that biomass of shrubs with a circular growth form correlates well with estimates of percent cover. Peek (1970) and Ohmann et al. (1976) measured crown diameter twice, at right angles to each other, and determined canopy area with the formulae for a circle or an ellipse, depending upon shrub shape. Murray and Jacobson (1982) also used the formula for circular area, but obtained a larger sample of crown diameter with four measurements taken at 45° angles. Ohmann et al. (1976) reported that crown area varied more than plant height or stem diameter, as assessed by standard deviation. Nonetheless, Peek (1970) concluded that regressions of annual production on crown area required 25 plants or less per species to be accurate within 10-18% of the

mean, 95% of the time. Shrub crown and production measurements required approximately 1 hour to collect for each species.

Estimates of crown volume are usually obtained by the product of height and crown area (Peek 1970; Moore and Bhadresa 1978; Guy 1981; Murray and Jacobson 1982) or by height and diameter products, assuming a conical shape (Burk and Dick-Peddie 1973; Bryant and Kothmann 1979). Zamora (1981), however, visually estimated crown volume belonging to one of eight percentage volume classes, within a vertical, three-dimensional plot. Required numbers of plots ranged from 7 to 1 084 for estimates to be achieved within 30% of the mean, 80% of the time, and 10% of the mean, 95% of the time, respectively. Sampling time per plot varied with vegetation structure and diversity, with the most difficult area consuming 3 hours to assess 50 plots (Zamora 1981).

Appropriate Techniques for Estimating Density

Assessment of biomass or production per shrub requires coincident evaluation of shrub density to obtain values of biomass or production per unit area. Although density per quadrats, or plots, may be estimated visually, Pechanec and Pickford (1937) reported high variability among estimates of three observers in grassland vegetation of southeastern Idaho. Consequently, density measurements are usually obtained by counting actual numbers of plants contained within quadrats, or by using one of the various plotless techniques summarized previously.

Oldemeyer and Regelin (1980) provided a good review of the literature that discussed the accuracy, precision, and efficiency of these various density determination techniques, and this forms the basis for much of the following discussion. Cottam and Curtis (1956) compared quadrats, closest-individual, nearest-neighbour, and point-centered quarter methods, and concluded that all distance measurements were equally accurate, assuming adequate sample size. However, the point-centered quarter method provided the least variable results, with more data per sampling point, subject to the least sampling bias. Although quadrat samples yielded accuracy similar to or greater than distance measurements, Cottam and Curtis (1956) concluded that such quadrat data are so variable, particularly in aggregated vegetation, that the number of required plots becomes virtually impossible to obtain.

Lyon (1968) compared 12 quadrats of different sizes and shapes with six distance measurements in a bitterbrush (Purshia tridentata) community of Montana, and found that only quadrats and the wandering quarter method (Catana 1963) produced estimates accurate to within two standard deviations of the actual population mean. Similar to Cottam and Curtis (1956), however, Lyon (1968) reported that between 62 and 17 926 samples were required, depending upon plot size and shape, to estimate shrub density within 50 plants -- approximately 10% of the actual mean per acre (0.4 ha) -- 95% of the time. Even the least variable quadrats required a search of 1.79-1.96 acres (0.72-0.79 ha) to obtain estimates within 10% of the known population value. Similarly, the wandering quarter method, which measures plant-to-plant distances along a meandering transect determined by a constant compass bearing and a 90^{o} angle of inclusion centred on successive plants, required over 600 samples on 1.44 acres (0.58 ha) to achieve desired accuracy. Such intensive sampling effort likely prohibits the use of any density estimate in practical field application (Lyon 1968), unless such estimates could be extrapolated to relatively large areas (e.g. 10 000 ha.

Distribution of shrubs in the landscape may be clumped or random, which further influences selection of an appropriate density measurement technique (Bryant and Kothmann 1979). Closest-individual, nearest-neighbour, random-pairs, and point-centered quarter methods all assume random distribution of shrubs in the landscape (Oldeymeyer and Regelin 1980). Aggregation tends to increase distances obtained with closest-individual, random-pairs, and point-centered quarter methods, while decreasing distances obtained by nearest-neighbour techniques (Cottam and Curtis 1956). The angle-order (Morisita 1957) and corrected-point-distance (Laycock and Batcheler 1975) compensate for aggregated distribution of plants by measuring additional distances at each sample point. For example, with the corrected-point-distance technique, three distances are enumerated. The point-to-nearest-plant distance provides unbiased estimates in random populations, while the two additional plant-to-plant distances correct for departure from randomness by supplying distances within clumps of plants near the sample point.

Laycock and Batcheler (1975) compared closest-individual, point-centered quarter, angle-order, and corrected-point-distance techniques in tussock grassland of New Zealand, and reported that only the corrected-point-distance

method produced estimates within 20% of the true mean in all populations tested. The closest-individual and point-centered quarter methods consistently vastly underestimated actual plant density in aggregated populations. The angle-order method also produced density estimates generally within 20% of the population mean, although this method overestimated density in extremely aggregated populations.

Similar results for an artificial dot population were provided by Boyd (1980), who demonstrated that corrected-point-distance and angle-order methods yielded estimates within $\pm$30% for all levels of aggregation. In contrast, estimates derived from point-centered quarter and random-pairs techniques underestimated density by 69 and 78%, respectively, in the most aggregated population. Moreover, the corrected-point-distance measurements required considerably less time to complete than the angle-order method (Boyd 1980).

Oldemeyer and Regelin (1980) investigated shrub distribution in Alaska, and indicated that all four species studied exhibited strong aggregation as determined by deviations from the Poisson distribution in at least two of three quadrat sizes. They reported that the closest-individual, random-pairs, and point-centered quarter estimates were low, while the nearest-neighbour technique vastly overestimated the shrub density. Only the point-centered quarter method provided a 95% confidence interval containing the population mean for one of three woody plant species.

In contrast, the angle-order and corrected-point-distance techniques developed for non-random plant distributions both produced 95% confidence intervals containing the true population density (Oldemeyer and Regelin 1980). Of these two equally accurate techniques, Oldemeyer and Regelin recommended use of the angle-order estimate because of its lower coefficient of variation relative to the corrected-point-distance method. Lyon (1968) also demonstrated that the angle-order method produced precise estimates, as only 44 sample locations were required to produce 95% confidence intervals within 10% of the sample mean. He further indicated, however, that this 95% confidence interval did not encompass the true population mean, and resulted in a precise but inaccurate estimate.

Such inconsistencies illustrate that no single density estimate technique may be generalized as best for shrub inventory programs. Lyon (1968) concluded that distance measurements based on random points are slightly more precise

than plant-to-plant or quadrat methods. However, such distance measurements are not suitable for non-random spatial distributions which characterize most shrub populations. Furthermore, Lyon (1968) reported that Morisita's angle-order and Catana's wandering quarter methods, both of which correct for non-random distribution, still underestimated true shrub density by 20 and 18%, respectively, compared to 33% underestimates for techniques assuming random distribution.

According to Oldemeyer and Regelin (1980), such trade-offs must be considered before the most appropriate technique for estimating shrub density is selected, because variable objectives suggest alternative techniques. They recommended, for example, the use of quadrat sampling when detailed, accurate information is required for all species in a stand; and the use of Morisita's (1957) angle-order method when more rapid, but equally accurate, information is required on a single woody species. For extensive shrub inventories, however, Laycock and Batcheler's (1975) corrected-point-distance technique offers the best theoretical and practical potential. Although they indicated that the corrected-point-distance technique required some additional theoretical refinements, they also concluded that any alterations in formulae will provide only slight, if any, practical improvements.

Appropriate Techniques for Estimating Utilization

Aldous (1944) visually assessed shrub utilization as heavy (50-100%), medium (10-50%), or light (trace-10%). Similarly, Walmsley et al. (1980) evaluated shrub utilization by two alternative techniques: 1) placement within one of five categories defining percentage of leaf and current twig growth browsed, and 2) identification of utilization form classes which describe eight categories of browse availability subsequent to browsing. Almost without exception, however, such visual estimates lack the accuracy required for intensive management, while clipping and weighing techniques are typically expensive and tedious (Lyon 1970). As well, simple enumeration of the proportion of browsed twigs may not correspond directly to utilization, because initial twig diameters and length of consumed twigs vary among plant species (Halls et al. 1970). Consequently, several alternative techniques, based upon relationships among utilization and associated shrub dimensions, have been developed to assess utilization more efficiently and accurately.

Based upon the relationship between diameter at point of browsing and biomass of twigs, first identified by Shafer (1963), Telfer (1969b) produced generally high coefficients of determination for weight of 38 shrub species. He recommended that such predictive relationships, when combined with twig counts, be used to evaluate shrub utilization by comparing browsed and unbrowsed paired plots, but cautioned that predictive equations may be highly variable depending on: 1) time of year the twigs are collected, 2) geographical location, 3) site conditions at time of sampling, 4) portion of shrub crown from which the sample is collected, and 5) age of twig. Although Telfer believed that some species could be grouped together within a single regression equation, all equations were reliable only within the range of twig diameter classes sampled.

Peek et al. (1971) regressed twig weight on diameter at point of browsing for eight shrub species on seven sites and reported that twig weights derived from a common equation differed from site specific equations by more than 20% in 25 of 44 cases. They concluded that variations in overstory canopy closure, browsing intensity, and soil moisture produced significant enough variation in twig diameter relationships to preclude use of a common predictor equation of twig weight based upon twig diameter. Basile and Hutchings (1966) similarly concluded that separate regression equations of twig weight on twig diameter may be needed for each site.

Potvin (1981) further indicated that diameters of sampled twigs do not always approximate diameter at point of browsing when twigs are collected because of (1) species variation in resin, which causes swelling in twigs following browsing, (2) variable dieback following browsing, (3) time of the year during which browsing occurs, and (4) time of the year during which measurement of twig diameters occurs.

Lyon (1970) investigated the relationship between twig diameter and weight of serviceberry (Amelanchier alnifolia), and also concluded that combined regression based upon all twigs differed significantly from regressions stratified by site, size of plant, and location of twigs on the plant. Nonetheless, he argued that such variability was acceptable from a practical perspective, and that reliable estimates of utilization for serviceberry could be obtained from 225 and 65 twigs for weight and length, respectively. Resultant predictive equations for population means were within 10% of the sample mean, 95% of the time. Reliable estimates of utilization could then be derived, assuming the following

data are collected: (1) percentage of the number of available twigs browsed, (2) mean diameters of a stratified sample of browsed twigs, and (3) mean lengths or weights of the twig parts remaining after browsing. Lyon (1970) further recommended that on-site regression equations be developed whenever possible.

Such regression equations can produce considerable savings in time. Provenza and Urness (1981) provided r^2 values of 0.85 and 0.94 for twig length and weight, respectively, regressed upon twig diameter. This accuracy of both regressions, when used to evaluate utilization, compared favourably with utilization assessed by length measurements before and after browsing by goats. Moreover, 28 man-days were required for direct measurement, compared to only 7 man-days to develop the regression equations.

Similarly, Ferguson and Marsden (1977) developed regression equations between unbrowsed twig length or weight and measurements of twig basal diameters. Estimates of overwinter utilization of bitterbrush were then obtained by comparing predicted, unbrowsed twig length or weight with measured residual twig length or weight, respectively.

Subsequent regression equations, based upon 47 site-years of data, each representing 30 shrubs, were field tested on four bitterbrush sites varying between 21 and 35% utilization. Percent utilization by length was estimated within 6 percentage points of actual values on all four sites. Percent utilization estimates by weight were within 5 percentage points on three sites, with the fourth site accurate within 8 percentage points. Based upon these results, Ferguson and Marsden (1977) recommended that acceptably accurate utilization estimates be obtained from specific site-year regression equations, particularly for length-diameter relationships. Such accurate regressions, they noted, could be developed from only 10 twigs collected from each of 20 shrubs, well distributed over the sampling area.

Jensen and Urness (1981) proposed an alternative technique for evaluating utilization, which requires neither direct before and after measurements nor development of regression equations. Utilization was estimated with the formula:

$$U = \frac{100\,(D_p - D_t)}{D_b - D_t}$$

where D_p equals mean twig diameter at point of browsing, D_t describes mean diameter of unbrowsed twig tips, assessed as the first measurable internode below the terminal bud, and D_b refers to mean basal diameter of browsed twigs. Mean percentage utilization, calculated directly from this formula, compared favourably with utilization determined by twig length differences. Cliffrose (Cowania stansburiana) and bitterbrush utilization differed by only 4 and 6%, as assessed by the two methods, respectively. In both cases the 95% confidence intervals for utilization based upon length differences and diameter measurements overlapped.

This technique requires that tips of unbrowsed twigs also be measured, although as few as 20 twig tips from a representative sample are required to provide sample means within 5% of the population mean at the 95% level of confidence (Jensen and Urness 1981). Utilization can then be assessed efficiently and accurately from post-browsing measurements alone, without the need for regression equations, during a single annual visit to the management or study area.

Appropriate Regressions and Transformations for Derived Estimates

Many of the shrub parameters discussed in previous sections depend upon estimates derived from regressions upon associated shrub dimensions. Such regressions are common to biological investigation, and most often assume linear, quadratic, semi-log, or log-log relationships between response and predictor variables. Log transformations, which correct for curvilinearity and heterogeneity of variance, are particularly common, as they generally increase the proportion of variability (r^2) of the response variable explained by the regression line (Sokal and Rohlf 1981).

Bryant and Kothmann (1979) evaluated these four models seeking to determine which provided the best estimates of annual production, as evaluated by highest r^2 values. The log-log function yielded highest coefficients of determination for robust shrubby species with relatively large variability in weight, while quadratic models proved best for shrubs with current growth consisting primarily of leaves rather than twig elongation. For other shrubs, none of the four models provided high predictability between annual production and crown volume either because of (1) irregular growth form, (2) insufficient

biomass to develop a good relationship, or (3) poor correlation between biomass and crown volume.

Bryant and Kothmann (1979) further indicated that the best predictive model varied with season, even for the same shrub species. Log-log equations generally proved superior from late summer through winter, likely because of variability in foliage among plants, while quadratic equations produced higher r^2 values during late spring and early summer.

Murray and Jacobson (1982) also reported increased r^2 values with quadratic regressions and log-log transformations. However, the standard error of the regression estimate was usually smaller with the linear regression model. Such standard errors of the regression estimate also varied among plant species, time of the year during which samples were collected, plus the parameter chosen as the predictor variable upon which biomass was regressed. Harrington (1979) demonstrated similar results, concluding that high correlation coefficients do not guarantee low standard errors of the regression estimate. Frequent examples existed where log transformations improved correlation at the expense of precision, prompting him to advise against extrapolation of such regression estimates to other plant communities.

Also stressing the importance of minimizing the standard error of regression estimates, Ohmann et al. (1976) concluded that linear and allometric relationships were superior to exponential and hyperbolic regressions of shrub biomass on associated plant parameters. Mountford and Bounce (1973), however, indicated that allometric functions, including log-log transformations, exhibit downward bias in estimates, regardless of sample size. They further stated that variances about logarithmic regression lines are particularly high for herbaceous and shrubby plant species, suggesting that such transformations be used with caution, even following use of a correction factor for bias.

According to Zar (1968), widespread use of allometric functions may be inappropriate because the log-log transformation is not statistically equivalent to linear models for least squares solutions. Furthermore, antilogarithms of values obtained from log-log regressions usually underestimate predicted values expressed in units of the original data set, which necessitates a subsequent correction factor for the regressions to be used for management purposes. Baskerville (1972), Beauchamp and Olson (1973), Crow and Laidly (1980), and Sprugel (1983) all concluded that weighted linear and weighted nonlinear models,

which displayed high goodness of fit, were acceptable alternatives to transformed allometric functions when assumptions of equal variance were violated. Weighted models avoid the transformation bias, but retain compatibility with the homogeneity of variance assumptions.

Blair (1958) noted that ratio estimates may be superior to linear models, in relation to homogeneity of variance assumptions, because ratio estimates assume variance about the regression line to be proportional to estimated green weight of browse. Such proportional variance is often true for data collected during shrub inventory programs. As well, ratio estimates avoid the anomaly of predicting positive or negative dry weight for sample quadrats with no shrubs. If a linear relationship passes through the origin and displays variance of points Y_i increasing proportionally with X_i, then ratio estimates are superior to least squares estimates of linear regression (Cochran 1977).

Ahmed et al. (1983) compared ratio estimation with linear regression for purposes of adjusting ocularly estimated plant biomass combined with double sampling. Both techniques provided comparable estimates of green and dry weights, even in situations where regressions produced negative intercepts. Although the assumption of homogeneity of variance was violated in most cases, the regression estimate provided coefficients of variation consistently less than those observed for ratio estimation. Ahmed et al. concluded that for all practical purposes, linear regression techniques yield better results than ratio estimation.

Literature addressing appropriate regressions and transformation is inconsistent and inconclusive. The "best" model remains elusive and unidentified. Hafley (1969) summarized this ambiguity by observing "... there is no algorithmic Solomon the scientist can turn to in order to absent himself from a decision ... scientific inference does not allow one to conclude that since two results differ, his preference is correct and the other is incorrect ... If one prefers to resort to a criterion of 'bestness', he must first define what 'he' means by 'best' and leave his audience to determine if his criterion meets their needs." For example, Forcella and Weaver (1977) noted that diameter-height products produced slightly higher r^2 values for regressions with Pinus albicaulis biomass than did diameter of breast height measurements alone. However, diameter at breast height measurements were recommended as the best regression model because of easier field measurements.

Selecting the most appropriate model based upon r^2 values is, however, often not mathematically acceptable, as neither coefficients of determination nor estimates of variability are directly comparable unless (1) response variables are expressed in the same units, and (2) regression models result from the same data set (Ezekial and Fox 1930; Kvalseth 1985). If these circumstances do not exist, a better comparison among models is provided by confidence intervals rather than r^2 values (J.P. Demaerschalk, Univ. B.C., pers. comm., 1985). Regardless of the impact on r^2 values, transformations should always occur when warranted statistically, such as to create homogeneity of variance. Necessarily, therefore, the most appropriate regression model cannot be predetermined without qualification, but must be based upon biological logic and statistical validity, plus acceptable levels of accuracy, precision, and cost -- determined, most likely, on a site-specific basis.

Appropriate Sampling Strategies

The primary objective of inventory sampling is to obtain estimates of population means within defined levels of accuracy and precision, with acceptable costs in time and money (McIntyre 1978). The ideal sampling method should strive to minimize complexity of field measurements and subsequent office calculations, while maintaining statistical reliability of inventory data (Rutherford 1979).

Simple random sampling, because of large sample variability and irregular distribution of shrubs, does not meet the objectives of desired accuracy and precision at acceptable cost (Blair 1958; Lyon 1968). Consequently, sampling locations should be allocated within strata predetermined to be relatively homogenous, with maximum variability among strata. Such stratification increases precision while simultaneously reducing sampling costs.

Following stratification, sampling points should be allocated within each stratum with cluster sampling, systematic sampling, variable probability sampling, or an optimal combination of them, depending upon (1) the relative costs of travelling to sampling points, and (2) sample variability within the stratum. Unqualified recommendations for the most appropriate sampling strategy within strata necessarily requires site-specific information regarding such costs and variability. Regardless of such considerations, however, double sampling a suitable proportion of sample units offers an excellent means of

obtaining reliable data at minimum cost (Wilm et al. 1944; Brown 1954; Blair 1958; Hilmon 1958; Cochran 1963; Hutchings and Schmautz 1969; McIntyre 1978; Ahmed and Bonham 1982).

Efficiency of double sampling depends upon the precision of the mathematical relationship between estimated and direct measurements, plus the relative costs of direct and estimated measurements. The primary question of double sampling therefore relates to the appropriate number of samples collected by estimated and direct techniques, respectively. If too many direct samples are collected, sampling costs remain high, while too few direct samples result in statistically unreliable data (Ahmed and Bonham 1982).

Formulae for determining proper allocation of sampling effort among direct and estimated samples are available in several sources (Cochran 1977; Ahmed and Bonham 1982; B.C. Ministry of Forests and Lands 1984). Optimal allocation, based upon these formulae, requires knowledge of (1) unit costs of direct and indirect measurements, (2) variability about the regression line developed between the direct and indirect measurements, and (3) the correlation coefficient between the direct and indirect measurements. Obviously, therefore, preliminary sampling is required to recommend an optimal allocation of effort in double sampling.

Preliminary sampling ideally compares the costs of those sampling techniques most likely to provide required levels of statistical accuracy and precision. Cluster sampling and systematic sampling both merit consideration for this preliminary sampling. No published data are currently available with which to determine which of these sampling strategies is most appropriate for British Columbia shrub communities. Almost certainly, the best sampling strategy will vary among shrub communities in different biogeoclimatic zones, as well as according to alternative managerial perceptions of required accuracy, precision, and budgetary constraints.

Preliminary estimates of sampling costs must include all inventory expenditures, including travel, field sampling, laboratory analysis of shrub material, and office commitments to data analysis and development of regression equations. For example, Wilm et al. (1944) reported that double sampling provided 37% more information than clipped plots alone, when compared on the basis of time spent in the field. However, improved efficiency of double sampling

declined to only 14% when comparisons of data yield were based upon combined time spent in field and office endeavours.

Hafley's (1969) observation that "no algorithmic Solomon" exists to identify the most appropriate regression model applies equally as well to selection of the "best" sampling strategy. The primary objective of shrub inventory is to provide reliable estimates of selected browse parameters, at acceptable cost, with precision adequate to establish managerially significant differences. The price of achieving required levels of precision and accuracy may be prohibitively high. Preliminary sampling is therefore necessary to ensure that inventory programs that might not achieve required objectives do not proceed (McIntyre 1978).

RECOMMENDATIONS FOR SAMPLING TECHNIQUES AND STRATEGIES

Specific recommendations for sampling techniques and strategies must clearly address inventory objectives for accurate, precise data collected at reasonable cost. Shrub inventory data must also satisfy the managerial needs identified by the B.C. Ministry of Forests and Lands (1982), including (1) determining levels of annual browse production available to livestock and wildlife, (2) monitoring changes in the browse resource, and (3) providing a means for determining the effectiveness of shrub management practices. The procedures for collecting shrub inventory data should also be simple to conduct, with a minimum of measurements required to meet the inventory and management objectives.

To meet the management objectives summarized above, both annual browse production and utilization should be documented within the shrub inventory program. Annual production permits resource managers to identify carrying capacity and to allocate known levels of available browse among browsing ungulates. Utilization is needed to refine estimates of annual browse production, as well as to provide inferences regarding anticipated changes in the browse resource. These estimates should be restricted to the height zones of browse available to livestock and wildlife, and should include current leaf and twig production of browse species, both deciduous and coniferous. For regions concerned primarily with winter range carrying capacity and utilization, deciduous leaves may be ignored.

Although the easiest way to inventory annual shrub production and utilization is with visual estimates, such techniques suffer from both observer and statistical bias, and therefore do not satisfy the requirement for known levels of accuracy and precision. Consequently, multi-phase sampling -- in which visually estimated auxiliary variables are combined with rigorously measured primary variables to predict production with prescribed levels of accuracy and precision -- provides the most efficient means of shrub inventory.

The previous assessments of sampling techniques suggest that estimates of annual production should not occur on individual shrubs, which would also require estimates of shrub density for the information to be expressed as available production per unit area. This procedure generates two sources of variability, one for the estimate of shrub production and another for the estimate of shrub

density. These combined sources of variability necessarily increase the sample sizes necessary to achieve desired accuracy and precision. Moreover, all density estimates, including those based upon distance measurements, are time consuming and subject to statistical bias in shrub populations with multiple levels of spatial aggregation.

The need for density estimates can be eliminated if annual production estimates are collected initially on a unit area basis rather than for individual shrubs. The provincial shrub inventory program should therefore strongly consider the procedure outlined by Zamora (1981). In this technique, three-dimensional plots, 1 m^2 horizontal and 3 m vertical, are systematically established along designated transects. Within the boundaries of each plot, total canopy volume of each shrub species are recorded within one of eight percentage volume classes. Availability of each species for browsing ungulates, expressed either as total canopy volume percentage or cubic canopy space per 3 m^3, should then be obtained by averaging the mid-point for each volume class recorded for each shrub species on all plots sampled. During a second phase of sampling, a subset of these volume estimates should be clipped and weighed for annual production. The canopy volume estimate then becomes an auxiliary variable for predicting annual production of sample units where no clipping and weighing occurs.

Shrub volume correlates well with biomass and production, and should provide good predictive relationships with generally lower coefficients of variation compared to other auxiliary variables (Peek 1970; Burk and Dick-Peddie 1973; Moore and Bhadresa 1978; Bryant and Kothmann 1979; Guy 1981; Murray and Jacobson 1982). Although Guy (1981) used an allometric predictive model, Burk and Dick-Peddie (1973) and Moore and Bhadresa (1978) favoured simple linear regression for predicting shrub biomass and production from volumetric measurements. Peek (1970) reported no appreciable change in correlations of annual production with volume, from using logarithmic rather than linear regressions, but Murray and Jacobson (1982) concluded that linear regressions were superior to all other predictive models tested. Nonetheless, simple or multiple regressions of browse production upon shrub volume are usually inappropriate, as such data normally seriously violate homogeneity of variance assumptions. Smaller estimates of variability associated with linear estimates

are misleadingly incorrect when derived from data sets with heteroschedasticity, or variances proportional to the mean.

Bryant and Kothmann (1979) clearly demonstrated that the best model depends on shrub species and season during which sampling occurs. The best predictive model(s) for browse production should therefore not be prejudged, but rather be developed from site/season/species-specific canopy volume and biomass data collected during the shrub inventory program. Despite this uncertainty, Ahmed et al. (1983) concluded that predictive equations based upon least squares estimates are generally more appropriate than alternative techniques, such as ratio estimation, because of statistically more valid coefficients of determination and lower estimates of variability. The regression problem of predicting non-zero values of shrub biomass when no shrubs are present can be eliminated by correcting the predicted mean to zero (Ahmed et al. 1983), or by sampling low volume shrubs.

Zamora (1981) recommended that shrub volume within three-dimensional plots be estimated within one of the following eight volume classes: 0-1, 1-5, 5-10, 10-25, 25-50, 50-75, 75-95, and 95-100%. Presumably he selected these boundaries to facilitate accurate, rapid identification of canopy volume classes even by relatively inexperienced observers. Such canopy volume estimates do not provide information regarding shrub production, which must still be determined by clipping and weighing. These clipped estimates of production are regressed upon visual estimates of canopy volume in a double sampling procedure. Clipping for annual browse production should be confined to twigs and leaves that are available to, and normally used by, ungulates of interest.

The precision of this regression estimate is increased with absolute estimates of canopy volume compared to volume classes (Ohmann et al. 1976). Therefore, the canopy volume classes proposed by Zamora (1981) should be discarded in favour of absolute percentage volume estimates. Dean et al. (1981) visually estimated shrub crown denseness, defined as percent foliage within the crown. No statistical differences ($p = 0.01$) occurred between mean values of visual estimates and point sampling of crown denseness along minimum and maximum shrub diameters. They therefore accepted visual estimates as accurate measures of crown denseness, particularly when calibrated with periodic point sampling. Similar potential likely exists for accurate, precise,

visual estimates of absolute shrub canopy volume, although no supporting examples were found in the literature.

Utilization of annual production should be determined with the method recommended by Jensen and Urness (1981). Measurements of twig diameters at the base and at the point of browsing are adjusted with diameters of adjacent unbrowsed twig tips to produce direct estimates of percentage utilization. Accurate estimates of utilization are derived from post-browsing measurements alone, with only a single visit to the sample site. These twig diameter measurements assess utilization without the laborious expense of clipping and weighing before and after browsing. Moreover, such direct utilization estimates also avoid the need for regression equations common to most other utilization assessment techniques.

Based upon a review of literature, Jensen and Urness (1981) concluded that twig diameter measurements correlated well with percent utilization by weight throughout all levels of utilization. Nonetheless, this conclusion remains unverified, while their recommended technique has been field tested only for bitterbrush and cliffrose. These two shrub species display cylindrically linear shoot growth, with needle-like leaves evenly distributed along the twig. Shrubs with more variable shoot and twig growth form(s) may be less suitable for the utilization techniques recommended by Jensen and Urness (1981).

Utilization estimates based upon twig diameter measurements usually assume that browsing occurs primarily by reduction of twig length. The recommendations of Jensen and Urness (1981), however, can be applied equally as well to utilization of leaves only, with twigs remaining intact, and to utilization by twig reduction. Utilization of leaves only can be derived from twig diameters (D_p) measured at the lower point of leaf stripping, equivalent procedurally to twig diameters (D_p) measured at the point of browsing. Leaf stripping, which includes the distal end of the twig, requires no adjustment in measurement location of twig tips (D_t).

If desired, absolute utilization can be derived with the product of percent utilization (Jensen and Urness 1981) and browse production, as determined by regressions of clipped browse production on visually estimated canopy volume. Browse production clipped during the second phase of sampling should be separated into twigs and leaves. Regressions among twig weight, leaf weight, shoot weight, twig length, and twig diameter can then be used to distinguish

among absolute estimates of various forms of browsing, such as utilization by twig reduction compared to utilization of leaves only.

Variability for absolute browse utilization includes the independent variabilities of annual browse production and percent utilization. Confidence intervals for absolute browse utilization derived from the product of these two independent variables should therefore be based upon the variance of products formulae summarized by Goodman (1960). If annual browse production is predicted with log-log regressions, then estimates of variability are asymmetric in the back-transformed scale. These back-transformed variances must be corrected before confidence intervals for products of utilization and annual browse production can be constructed (Schwab 1985).

Sampling strategies most appropriate for estimates of annual browse production and utilization should, wherever possible, be consistent with procedures currently being developed by the Ministry of Forests and Lands for rangeland inventory. Such consistency must also be tempered by the primary objectives of browse inventory for (1) estimates of carrying capacity, and (2) monitoring of changes in the browse resource. The following sampling strategies are recommended to achieve these objectives within the general framework of current rangeland inventory procedures:

1. The inventory area should be stratified according to forest cover types, ecosystem associations, or some other meaningful criteria that reduce the variability of estimates for browse production and utilization within strata.

2. Primary sample units should be selected at random within each stratum.

3. Secondary sample units, within each randomly selected primary sample unit, should be clustered to reduce travel costs associated with sampling.

4. Within each secondary sample unit, plots for visual estimation of shrub canopy volume (auxiliary variable) should be located systematically along transects, further reducing sampling costs and increasing precision in random plot location. Transects should occur within clumps or aggregations of shrubs, if non-randomly distributed.

5. Double sampling for annual browse production (primary variable) should be allocated according to variable probability proportional to size (Cochran 1977). This procedure, based, for example, on five categories of 20% canopy volume increments, stratifies clipping effort to produce a more precise regression estimate between visually estimated canopy volume and clipped annual production.

6. Plots should be clipped for annual browse production when the information is most suitable for estimates of carrying capacity, such as during peak browse production or at the beginning of the winter period.

7. Browse utilization should be measured following seasonal browsing by livestock, and/or when wildlife leave important winter ranges.

8. Twigs marked for utilization measurements should be systematically located on shrubs to reflect position variability within the zones of availability to browsing animals.

9. Estimates of annual browse production should be based on at least 3 years of data to reflect annual variability.

10. Plot transects should be marked permanently for long-term monitoring. Utilization should be measured approximately once every 5 years.

Readily available are formulae for determining optimal numbers of primary and secondary sampling units, appropriate proportions of measured primary variable samples to visually estimated auxiliary samples, and allocation of clipped plots according to variable probability proportional to size (Cochran 1977; B.C. Ministry of Forests and Lands 1982; Ahmed and Bonham 1983).

Potential Sources of Error and Bias

Jolly (1954) observed that data derived from sampling biological systems suffer from two sources of variability: 1) sampling error, wherein sample estimates deviate unpredictably from the population mean, and 2) bias, which describes systematic deviations of sample means from population means, result-

ing from an inappropriate sampling strategy or technique. Assessment of annual shrub production and associated parameters nearly always include both error and bias, which must therefore be identified and understood if successful shrub inventory programs are to be developed.

The most obvious source of random error is that associated with the inherent variability that characterizes all shrub parameters. No individual sample perfectly reflects the true average values of the population from which the sample is drawn. Such random error is reduced with appropriate sampling allocation strategies, and by increasing sample size.

Other sources of error, however, persist even with appropriate sampling strategies and adequate sample size. For example, the literature suggests that shrub measurements vary depending upon shrub species, plant phenology, and degree of dessication (Dean et al. 1981), genetic variability within species from region to region (Telfer 1969a; Lyon 1970); environmental site conditions (Telfer 1969a, 1969b); annual growing conditions (Stone and Crawford 1981); shrub size (Lyon 1970); position on shrub from which samples are collected (Telfer 1969b; Lyon 1970); season of year during which samples are collected (Telfer 1969b; Bobek et al. 1979; Potvin 1981); variations in overstory canopy closure (Peek 1970); browsing intensity (Peek 1970); variable shrub response to browsing (Potvin 1981); and season of year during which browsing occurs (Potvin 1981).

Bias occurs either from statistical sources or from biases associated with personal decisions related to locations or collecting data from sampling units. Jolly (1954) concluded that bias is virtually certain to be present where the choice of sampling unit, or the values of recorded data, are influenced by subjective decisions. Such bias occurs both within and among individual samplers and increases with personal fatigue and harsh field conditions. Subjective bias also results when the boundaries of plots are not defined accurately, or when sampling procedures and formats are not rigorously standardized and clearly explained to field personnel.

Statistical bias arises primarily when sampling procedures violate statistical requirements. For example, when shrubs display clumped or uniform spatial distribution, sampling strategies that assume random distribution should be abandoned. Procedural, statistical bias occurs when sample means, gathered from different sampling units or strata, are not weighted proportionately to sampling intensity before an overall population mean is calculated. Similarly,

the use of regression equations that violate assumptions of linearity, homogeneity of variance, or a demonstrated need for transformation to log-log relationships reduces the reliability of predictive equations because of statistical and procedural biases.

This list of potential sources of error and bias, even though incomplete, creates a formidable challenge to shrub inventory programs. Careful planning and conscientious data collection can reduce -- but may not eliminate -- either problem. This fact indicates that utilization and regressions of measured annual browse production on visual estimates of shrub canopy volume cannot be extrapolated confidently to other regions or sites within the same or similar biogeoclimatic zones. Rather, precise and accurate assessments of shrub parameters depend upon site-, season-, and species-specific estimates, measurements, and regressions.

Anticipated Levels of Accuracy and Precision

McQuisten and Gebhardt (1983) reviewed the importance of inventory data to the decision making process in resource management. These authors stressed that although inventory data can be quite useful, they can also be misleading, depending upon how the data are generated and interpreted. For example, data can be inaccurate and imprecise, having both random and systematic errors; they can be precise but inaccurate, having systematic errors; and they can be both accurate and precise, having neither random nor systematic errors.

If land management decisions are to be based upon these inventory data, then decision makers must be provided with an explicit level of statistical confidence in the reliability associated with the data. Without such confidence and reliability, the data may be misinterpreted, or ascribed greater weight in the decision making process than actually warranted.

Theoretically, inventory data can be both accurate and precise. However, this ideal is seldom possible for extensive inventory programs. Therefore, it becomes necessary to define acceptable levels of confidence in the data. By way of example, McQuisten and Gebhardt (1983) suggested that 95% confidence is required for litigation purposes, while 85% is suitable for land management decisions. Reports based on data with 75% confidence should contain qualifications, while information providing less than 75% confidence may either be used for general information purposes only, or discarded. Similarly, the B.C. Ministry

of Forests and Lands (1984) recommends that range management units or inventory types of high, medium, and low management priority should be assessed at 80% confidence within 20, 25, and 30% of true population means, respectively.

Sampling precision and accuracy are direct functions of sampling intensity and population variability, and thus any desired levels of precision and accuracy, including those summarized above, are technically possible to attain. Indeed, regression equations presented in the literature, which describe relationships between estimated shrub biomass and volume with associated shrub parameters, generally display accuracy and precision greater than those required by the B.C. Ministry of Forests and Lands (1984). Similarly, Zamora (1981) provided adequate precision for estimates of crown volume, while Jensen and Urness (1981) also demonstrated acceptably accurate estimates of shrub utilization at the 95% level of confidence.

Such desired levels of accuracy and precision, however, may be extremely costly, particularly for inventory programs where samples often display high variability. Consequently, the obvious usefulness of highly accurate and precise data must also be weighed in terms of financial constraints. For example, based upon $20 per sample, the cost of estimating density of bluebunch wheatgrass (Agropyron spicatum) within 10% accuracy at 95% confidence equalled $3480 compared to only $440 for estimates providing 20% accuracy at the 90% level of confidence (B.C. Ministry of Forests and Lands 1984).

Such financial savings associated with reduced accuracy and precision are desirable, and permit more extensive shrub inventory programs compared to those which pursue greater statistical reliability. Preliminary sampling is necessary, prior to implementation of intensive shrub inventory activities, to assess the relative costs associated with estimates of shrub parameters at prescribed levels of desired accuracy and precision. Levels of accuracy and precision required by the B.C. Ministry of Forests and Lands (1984) are undoubtedly possible. Preliminary sampling will assess the costs associated with such accuracy and precision. This information is necessary to determine affordable levels of inventory activities, particularly in allocating inventory effort within high, medium, and low priority management regions and districts. In many situations, browse production and utilization estimates at acceptable levels of accuracy and precision may be economically prohibitive.

Appropriate Sample Sizes and Shapes

Historically, line transects have provided a common technique with which to assess shrub dominance and botanical composition (Canfield 1941), particularly within a double sampling format (Wilm et al. 1944). Canfield (1941) initially proposed crown canopy intercept of the transect line as a rapid, statistically reliable measure, relatively free from observer bias. Adequate transect lengths and numbers varied directly with heterogeneity of vegetation (Canfield 1941). Such long, rectangular transects, or plots, produce less statistical variability than square plots of uniform size (Bobek and Dzieciolowski 1972). Too great an elongation, however, increases the "edge effect", resulting in greater sample bias when observers are deciding which plants are in the plot (Grieg-Smith 1983).

Oldemeyer and Regelin (1980) compared estimates of density obtained within 1-, 5-, and 10-m^2 plots, and reported that relative accuracy and precision varied with density measurement technique and plant species. Generally, however, 5- and 10-m^2 plots yielded comparable results, prompting Oldemeyer and Regelin to recommend the former because of reduced field time for plot enumeration. Similarly, Bobek and Dzieciolowski (1972) advocated the use of circular rather than rectangular plots for vegetation lower than 1 m as circular plots are more quickly and accurately delineated because of reduced linear distance (Ahmed et al. 1983). Grieg-Smith (1983) reviewed density estimate research and concluded that any conveniently sized plot was sufficient for randomly distributed vegetation. Small plots generally provided smaller standard errors as a proportion of the sample mean in non-randomly distributed vegetation.

Lyon (1968) compared square and rectangular plots of various sizes to estimate shrub density and concluded that all methods required unreasonably large samples to attain acceptable precision. Cottam et al. (1953) also warned that extreme variability of random populations often generates results so imprecise -- regardless of technique employed -- that any conclusions based on small samples may be completely inappropriate.

Because of unknown variability in estimates of annual browse production, utilization, and spatial distribution patterns of vegetation, generalized recommendations for appropriate sample sizes and shapes are unwarranted (Bobek and Dzieciolowski 1972). Undoubtedly, the most suitable size and shape of plot

depends upon specific vegetation types being studied, acceptable levels of accuracy and precision, plus ease of sampling (Ahmed et al. 1983).

Therefore, the current recommendations for estimates of annual browse production, utilization, and canopy volume should initially adopt the plot size and shape recommended by Zamora (1981). These three-dimensional plots measure 1 m^2 in horizontal directions, with a 3-m vertical dimension. Zamora (1981) believed that the 1-m^2 horizontal measurement provided adequate sampling of widely spaced shrubs, while permitting ease of observation and manoeuvering in dense brush. The vertical dimension of 3 m exceeded the normal browsing height of deer, elk, and moose. He noted, however, that plot size and shape should be adjusted according to vegetation characteristics and sampling objectives.

Stauffer (1983) presented tables that summarize adequate sample size as a function of estimated coefficient of variation, and prescribed sampling errors at specified levels of confidence. These tables show adequate sample sizes ranging between 2 and 43, needed to achieve estimates within 20% of the sample mean at the 80% level of confidence, as the coefficient of variation increases from 1 to 100%. Such sample sizes are not likely to be financially prohibitive within a shrub inventory program. Stauffer's (1983) recommendations, which assume random sampling, do not consider cost, plot size and shape, vegetation structure and pattern, or variability of regression lines developed from double sampling. All of these factors, including allocation of sampling locations, must be considered before appropriate sample sizes and shapes are recommended. Failure to identify such factors clearly may lead to inconclusive, unreliable information (B.C. Ministry of Forests and Lands 1984).

RESEARCH NEEDS

Before intensive shrub inventory activities are begun, preliminary sampling should be conducted to assess the relative costs, accuracy, and precision of recommended sampling strategies and techniques. Such preliminary investigations should provide specific information on the following items:

1. optimal proportion of primary and secondary sample units.

2. minimum sample size necessary to achieve prescribed levels of accuracy and precision of sample means for (i) clipped estimates of annual browse production, and ii) twig diameter measurements as indicators of utilization, including woody and leafy material.

3. optimal allocation of clipped annual browse production within canopy volume increments, according to variable probability proportional to size.

4. assessment of shrub canopy volume estimates as precise, accurate predictors of annual browse production.

5. assessment of twig diameter measurements as precise, accurate predictors of browse utilization, including woody and leafy material.

6. assessment of a three-dimensional, 3-m^3 plot as suitable for the physiognomy and spatial distribution of shrubs inventoried in British Columbia.

7. development of regression equations between auxiliary and primary shrub variables assessed within a double sampling format. Such equations provide preliminary correlation coefficients and estimates of variability, which are required to determine cost efficient proportions of annual browse production measurements during phase two samples, compared to visual estimates of shrub canopy volume recorded during phase one sampling.

These recommendations for preliminary sampling should be considered as procedural preparation rather than experimental research. This preparation provides a logical framework and quantitative foundation upon which an efficient shrub inventory program is built. Ideally, preliminary sampling should occur in all those shrub communities exhibiting variabilities that may alter optimal allocation of sampling units, optimal proportion of direct and indirect measurements, minimum sample size, or the relationships among twig diameters, canopy volume, annual browse production, and utilization. Practically, however, preliminary sampling should be restricted to select groups of shrub communities considered either representative or important from a managerial perspective.

Logistically, preliminary data may be collected simultaneously with the initial stages of the shrub inventory program; but these data must be analyzed and evaluated immediately so that revised sampling and measurement techniques can be incorporated before the second field season of inventory activities. These preliminary assessments must not be ignored, as they are essential for optimal allocation of funds and personnel. Moreover, preliminary sampling will clearly establish whether desired levels of accuracy and precision can be attained at acceptable cost.

IMPLEMENTATION PROCEDURES

Preliminary sampling constitutes a necessary first step towards achieving reliable information, pertinent to resource managers at acceptable cost. The following recommendations are provided to facilitate efficient collection of data during intensive shrub inventory programs.

1. Presumably, all forest districts and biogeoclimatic zones where shrubs constitute an important forage source for livestock and wildlife will benefit from a shrub inventory program. Nonetheless, managerial and information priorities, plus financial and personnel resources, vary among forest districts. The shrub inventory program should assess these priorities carefully to identify those forest districts and biogeoclimatic zones where shrub inventory information is needed most urgently to improve livestock and wildlife management programs. The shrub inventory program should then allocate sampling effort proportionally among these districts and zones to provide the greatest managerial and information return to the inventory dollar.

2. Homogenous shrub communities, as determined from aerial photographs, should be mapped within each high priority forest district and biogeoclimatic zone.

3. Annual browse production and utilization should be restricted to managerially important shrub species. Through consultation with local resource managers such species can be identified, and will likely vary among forest districts and biogeoclimatic zones.

4. Regression equations between clipped annual browse production and visually estimated shrub canopy volume should be developed separately for each managerially important shrub species. Although the same regression may be appropriate for all species displaying similar growth form, separate equations are necessary to reflect observer, site, and seasonal variabilities.

5. Sampling for annual browse production and utilization should not be restricted to climax or specific stages of plant succession, but rather should represent current production, availability, and utilization of shrubs within selected land management units.

6. Shrub inventory field personnel should receive a minimum of 1 week's training, followed by periodic site inspections. Such verification is required to ensure consistent inventory data, directly comparable among individual samplers and forest districts.

7. Inventory data should be analyzed quickly and its accuracy, precision, and associated costs assessed. Analytical results will indicate needed changes in sampling strategies and techniques, which can be incorporated to improve statistical and financial efficiency of subsequent field seasons. It is imperative to note that the specific recommendations for plot size and shape, twig diameter measurements, clipped biomass, and canopy volume estimates are still unproven on an extensive inventory basis. Although offering excellent potential for cost-efficient shrub inventories, all data collected during preliminary sampling must be quickly and thoroughly analyzed to ensure that inventory objectives for accuracy and precision are being attained.

SUMMARY

Detailed summaries of recommendations for specific sampling strategies and techniques are contained in previous sections of the text. The following list summarizes those conclusions most relevant to the terms of reference of this problem analysis.

1. Shrub inventory programs should assess annual production to achieve desired allocation of browse among browsing animals.

2. Shrub inventory programs should assess utilization to adjust estimates of available browse, and to provide inferences regarding anticipated changes in the browse resource.

3. Browse production should be determined within a double sampling program which includes visual estimates made during first phase samples and measured values obtained in second phase samples.

4. Visual estimates should include absolute assessments of shrub canopy volume.

5. Direct measurements should include clipping and weighing for annual browse production. Utilization should be determined with direct measurements of (i) browsed twig diameters at base and point of browsing, and (ii) unbrowsed twig diameters at the first measurable internode below the terminal bud.

6. Visual estimates and direct measurements should occur initially within three-dimensional plots measuring 1 m^2 in horizontal directions, with a 3-m vertical dimension.

7. The same regression equation(s) between estimated auxiliary and measured primary variables may be appropriate for shrub species with similar growth

form(s). Nonetheless, separate equations are likely necessary to reflect observer, site, and seasonal variabilities.

8. The most appropriate transformation and regression models between measured and estimated shrub variables can be determined only with preliminary data that confirm the statistical assumptions and functional relationships appropriate for each alternative model.

9. Visual estimates and direct measurements should be collected only for those shrub species identified as managerially important.

10. The inventory area should be stratified to reduce the variability of estimates for browse production and utilization within strata.

11. Secondary sample units should be clustered at primary sample units, selected randomly within strata.

12. Plot locations for double sampling should be located systematically along transects within clumps or aggregations of shrubs, if non-randomly distributed.

13. Estimates of annual browse production per volumetric unit preclude the need for time-consuming, statistically biased density estimates.

14. Preliminary sampling is necessary to determine minimum sample sizes required to measure annual browse production and utilization at desired levels of accuracy and precision.

15. Preliminary sampling is required to assess visual estimates of shrub canopy volume as accurate, precise predictors of clipped annual browse production.

16. Preliminary sampling is required to determine the most cost-efficient proportion and allocation (variable probability sampling) of clipped browse

production (primary variable) to visually estimated canopy volume (auxiliary variable).

17. Field personnel should receive adequate training to provide consistency and comparability of inventory data.

18. Specific recommendations for plot size and shape, twig diameter measurements, clipped browse production, and canopy volume estimates remain unverified on an extensive inventory basis. Results from preliminary sampling must be analyzed immediately to ensure that prescribed accuracy and precision are being attained.

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GLOSSARY

Accuracy:	The nearness of a measurement to the actual value of the variable being measured.
Allometric:	A growth curve characteristic of many organisms described by the regression equation $Y = aX^b$.
Auxiliary variable:	A variable used to provide a precise estimate of the primary variable of managerial interest.
Bias:	Sampling bias occurs when certain individual measurements have a greater chance to be included than others. Statistical bias occurs when the expected value of the statistic differs from the population parameter.
Biomass:	The total amount of living, aboveground material, per plant or per unit area, at a specific point in time.
Browse:	That part of annual leaf and twig growth of shrubs, woody vines, and trees, potentially available for animal consumption.
Coefficient of determination:	A measure of the proportion of total variability in a response variable accounted for by regression upon the predictor variable(s).
Coefficient of variation:	A relative measure of variation, equal to the sample standard deviation expressed as a percentage of the sample mean.
Correlation coefficient:	Expresses the intensity of positive or negative association between two variables.

Confidence: An expression of accuracy of sample estimates, usually assessed by confidence intervals, a specified proportion of which, such as 95% confidence intervals, contain the true population parameters.

Cover: The area of ground surface included in a vertical projection of plant canopies.

Density: The number of individuals per unit area.

Error: See Variance.

Frequency: The ratio between the number of sample units containing an individual and the total number of sample units.

Precision: The closeness to each other of repeated measures of the same quantity.

Predictor variable: Any variable used in regression equations to predict the value of a yield or response variable. Synonymous with independent variable.

Production: The total biomass increment per plant, or per unit area, during a specific time period, such as annual production.

Quadrat: Sampling units with defined boundaries. Although technically square, quadrats may also be circular, triangular, oblong, or rectangular.

r: The correlation coefficient.

r^2: The coefficient of determination.

Regression:	A causative relationship between a response and a predictor variable. Regressions may be of many kinds, including linear, quadratic, cubic, and curvilinear.
Shrub:	A plant with persistent woody stems and a relatively low growth habit, which generally produces several basal shoots instead of a single bole.
Standard deviation:	The square root of variance.
Utilization:	The proportion of the current year's growth or production that is removed by grazing or browsing animals.
Variance:	The mean squared deviations of observations about a sample mean. Synonomous with experimental, or unbiased sampling error.